


The magnetic field evolution of ULX NuSTAR J095551+6940.8 in M82—a legacy of accreting magnetar

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ABSTRACT

Ultra-luminous X-ray sources are usually believed to be black holes with mass about $10^{-3}M_{\odot}$. However, the recent discovery of NuSTAR J095551+6940.8 in M82 by Bachetti et al. shows that it holds the spin period $P = 1.37$ s and period derivative $\dot{P} \approx -2 \times 10^{-10} \text{ s s}^{-1}$, which provides a strong evidence that some ultra-luminous X-ray sources could be neutron stars. We obtain that the source may be an evolved magnetar according to our simulation by employing the model of accretion induced the polar magnetic field decay and standard spin-up torque of an accreting neutron star. The results show that NuSTAR J095551+6940.8 is still in the spin-up process, and the polar magnetic field decays to about 4.5×10^{12} G after accreting $\sim 10^{-2.5}M_{\odot}$, while the strong magnetic field exists in the out-polar region, which could be responsible for the observed low field magnetar. The ultra luminosity of the source can be explained by the beaming effect and two kinds of accretion—radial random accretion and disk accretion. Since the birth rate of magnetars is about ten percent of the normal neutron stars, we guess that several ultra-luminous X-ray sources should share the similar properties to that of NuSTAR J095551+6940.8.

Key words: accretion: accretion disks – binaries: close – X-rays: stars– stars:magnetars

1 INTRODUCTION

Ultra-luminous X-ray sources (ULXs), also named super-Eddington sources or super-luminous sources, were discovered by Einstein Observatory in 1980's (Fabbiano 1989). They are usually thought as the point sources with luminosity about $10^{39} \text{ erg s}^{-1}$ or above in the accreting systems. Assuming that the isotropic emission is with Eddington limit, ULXs may be black holes whose mass go beyond those of the stellar black holes (Makishima et al. 2000; Feng and Soria 2011; Pasham et al. 2014; Weng et al. 2014). Recently, an ULX NuSTAR J095551+6940.8 in the nearby galaxy M82 was discovered by Bachetti et al. (2014), which may be the counterpart of NuSTAR J095551+6940.8 (Feng & Kaaret 2007; Bachetti et al. 2014). The spin period ($P = 1.37$ s) and period derivative ($\dot{P} \approx -2 \times 10^{-10} \text{ s s}^{-1}$) prove that it is an accreting neutron star (NS) in high mass binary system (HMXB) (Bachetti et al. 2014), which sheds a doubt on that all ULXs are accreting black holes.

Studying on NuSTAR J095551+6940.8 would help us understand various distinctive characteristics of ULXs, and how an accreting neutron star can be explained as an ULX. To this point,

many researchers have paid much attentions. Shao and Li (2015) modeled the formation history of NuSTAR J095551+6940.8. They suggested that NS in X-ray binary system might significantly contribute to ULX population. High-mass and intermediate-mass X-ray binary pulsars dominated the ULX population in M82 and Milky way like galaxies, respectively. Kluźniak and Lasota (2015) pointed out that NuSTAR J095551+6940.8 would become a millisecond pulsar within 10^5 yr, which provided a new way of millisecond pulsar formation in HMXBs. Dall'Osso et al. (2015) proposed that the favorite magnetic field of NuSTAR J095551+6940.8 was $\sim 10^{13}$ G based on the physical considerations and the observed properties of the source. Mushtukov et al. (2015) pointed out that the surface magnetic field strength was $\sim 10^{14}$ G for NuSTAR J095551+6940.8 with the observed luminosity $\sim 10^{40} \text{ erg s}^{-1}$, but could not be too large due to the propeller effect. Eksi et al. (2015) showed that its dipole magnetic field was as strong as 6.7×10^{13} G according to the torque equilibrium condition. As expected, it could hold even stronger multi-pole field that suppresses the scattering cross section and increases the Eddington luminosity (Eksi & Alpar 2003, Canuto et al. 1971). Moreover, Tong (2015a, 2015b) proposed that NuSTAR J095551+6940.8 might be a magnetar in an accreting system, which favored the idea that magnetars were descen-

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dants of high mass X-ray binaries (Bisnovatyi-Kogan & Ikhsanov 2015).

Magnetar is always an isolated NS with the super-strong magnetic field about 10^{14-15} G, which is always thought to be the candidate of soft gamma repeater or anomalous X-ray pulsar (Duncan & Thompson 1992; Kouveliotou et al. 1998; Mereghetti 2008; Bisnovatyi-Kogan & Ikhsanov 2014; Olausen & Kaspi 2014). Until now, there is no evidence that indicates magnetar exists in binary system, though it could not be excluded from the theoretical ground. It has been proposed that the accreting magnetar in the close binary system could be used for interpreting the slow rotating NS in 4U 2206+54 (Ikhsanov & Beskrovnaya 2010). However, magnetars in binary systems should be the rare case, since the birth rate of magnetar is only ten percent of the normal NS (Lorimer 2008). Therefore, it can be imagined that a successful explanation of the status of NuSTAR J095551+6940.8 can help us understand NS as an ULX that exists in binary system.

By means of the accretion induced NS magnetic field evolution model (Zhang & Kojima 2006) and NS spin-up formula by Ghosh and Lamb (1979), we calculated the evolution of the magnetic field and spin period of a magnetar with the appropriate initial condition to make the evolved spin period fit the status of NuSTAR J095551+6940.8. With the result, we compare its evolutionary track of the magnetic field and spin period with those of the observed pulsar in binary systems. The paper is organized as below: the model is described in Section 2; calculations and B-P diagram are presented in Section 3; and the discussion and summary are included in section 4.

2 THE MODEL

The model of accretion induced magnetic field decay of a NS was proposed by Zhang and Kojima (2006). It is assumed that the accretion material is channeled by the strong magnetic field to the polar cap, where the field lines are expelled towards the out-polar regime and enter into the magnetic equator region. As a result, the strength of the polar field decays and the piled-up stronger out-polar field lines at equator region are mostly squeezed into the inner crust of the NS. The analytical form of the polar field decay of a NS is obtained,

$$B = \frac{B_f}{\{1 - [C/\exp(y) - 1]^2\}^{\frac{1}{4}}}, \quad (1)$$

where $y = 2\Delta M/7M_{\text{cr}}$ is a ratio parameter of the accretion mass ΔM and the crust mass $M_{\text{cr}} \sim 0.2M_{\odot}$ of a NS. $C = 1 + (1 - X_0^2)^{\frac{1}{2}} \sim 2$ is with $X_0^2 = (B_f/B_0)^{4/7}$, where B_0 is the initial field at the beginning of the accretion, and B_f is the bottom magnetic field while the magnetosphere is compressed onto the surface of NS,

$$B_f = 4.5 \times 10^8 \text{ (G)} \cdot \dot{M}_{18}^{\frac{1}{4}} m^{\frac{1}{4}} R_6^{-\frac{5}{4}} (\phi/0.5)^{-\frac{7}{4}}, \quad (2)$$

where \dot{M}_{18} , m and R_6 are the NS accretion rate in units of 10^{18} g s^{-1} , the mass in solar mass and radius in units of 10^6 cm , respectively. In detail, with the condition of the magnetosphere radius R_M matching the NS radius R , i.e., $R_M = R$, the bottom field B_f is achieved. Generally, R_M is related to the Alfvén radius R_A

$$R_M = \phi R_A, \quad R_A = 3.2 \times 10^8 \text{ (cm)} \cdot \dot{M}_{17}^{-\frac{2}{7}} \mu_{30}^{\frac{4}{7}} m^{-\frac{1}{7}}, \quad (3)$$

where μ_{30} is the magnetic moment in units of 10^{30} g cm^3 and the preferred parameter $\phi \sim 0.5$ is usually considered (Ghosh & Lamb 1979; Shapiro & Teukolsky 1983; Frank et al. 2002).

The evolution of the spin period of a NS in the accretion phase described by Ghosh & Lamb (1979) is

$$-\dot{P} = 5.8 \times 10^{-5} \text{ (s yr}^{-1}\text{)} \cdot [m^{-\frac{3}{7}} R_6^{\frac{12}{7}} I_{45}^{-1} B_{12}^2 (PL_{37})^2 n(\omega_s), \quad (4)$$

where I_{45} is the moment of inertia in units of 10^{45} g cm^2 and L_{37} is luminosity of the accreting NS in units of $10^{37} \text{ erg s}^{-1}$; B_{12} is the polar magnetic field in units of 10^{12} G ; The dimensionless torque $n(\omega_s)$ is

$$n(\omega_s) = 1.4 \times \left(\frac{1 - \omega_s/\omega_c}{1 - \omega_s} \right), \quad (5)$$

which is associated with the fastness parameter $\omega_s \equiv \Omega_s/\Omega_k$, where $\Omega_s = 2\pi/P$ is the spin frequency of the NS. Ω_k is the Keplerian frequency at the radius R_M , ω_c is the critical value in the range of $0.2 - 0.9$ (Ghosh & Lamb 1992).

During the NS spin-up process, the spin frequency will be constrained by the Keplerian orbital frequency of the accreting material at the magnetosphere radius. Therefore, the minimum spin period corresponding to the field strength can be described by the equation of the spin-up line (or equilibrium period line) with condition of the spin frequency being the same as the Keplerian frequency at the magnetosphere radius (Bhattacharya and van den Heuvel 1991):

$$P_{\text{eq}} = 0.89 \text{ (s)} \cdot B_{12}^{6/7} m^{-5/7} \dot{M}_{18}^{-3/7} R_6^{16/7}. \quad (6)$$

The corresponding line of Eq.(6) has been plotted as the solid line in Fig.1 with the Eddington rate and standard NS parameters, e.g. $m = 1.4M_{\odot}$ and $R = 10 \text{ km}$.

3 THE MAGNETIC FIELD OF NuSTAR J095551+6940.8

As an accreting NS, NuSTAR J095551+6940.8 is a unique source since its luminosity and period variation ($L \sim 10^{40} \text{ erg s}^{-1}$ and $\dot{P} \approx -2 \times 10^{-10} \text{ s s}^{-1}$) are higher than that of NS in HMXBs ($L \sim 10^{36-38} \text{ erg s}^{-1}$ and $\dot{P} \sim 10^{-12} \text{ s s}^{-1}$) (Ghosh & Lamb 1979; Shapiro & Teukolsky 1983; Bildsten et al. 1997; Frank et al. 2002; Liu et al. 2007). So its evolution history may be different from that of the usual X-ray pulsars in HMXBs. The low field magnetar SGR 0418+5729 had been discovered with the dipole magnetic field less than $7.5 \times 10^{12} \text{ G}$ and the strong field of $B \sim 10^{14-15} \text{ G}$ which might be internal (Rea et al. 2010, 2012; Turolla et al. 2011). Therefore, we simulate the magnetic field and spin period evolution of a magnetar based on the model of accretion induced polar magnetic field decay of a NS (Zhang & Kojima 2006). During the simulation, we set the initial condition (accretion rate, initial magnetic field and spin period) and try to find a magnetar with the evolved values of spin period and period derivative to be the same as those of NuSTAR J095551+6940.8 that is spinning up now.

The spin period of the observed magnetar is usually about 10 second with the estimated age 10^4 yr (Mereghetti 2008; Bisnovatyi-Kogan & Ikhsanov 2014; Mereghetti et al. 2015). Since the companion mass of NuSTAR J095551+6940.8 is more than $5.2M_{\odot}$, its main sequence stage before evolving to feed the accretion disk would last for about one million years, during which the magnetar might spin down to about 100 seconds due to the period and lifetime relation of the magnetic dipole emission as $P \sim \sqrt{t}$ (Shapiro & Teukolsky 1983). So the initial spin period (P_0) of the accreting magnetar is chosen to be 100 s. The initial magnetic field is set to be the usual values of magnetar as $3.0 \times 10^{14} \text{ G}$. Employing the evolution formula of B and P given in Section 2, the evolved path of B and P for NuSTAR J095551+6940.8 are calculated and plotted in Fig.1.

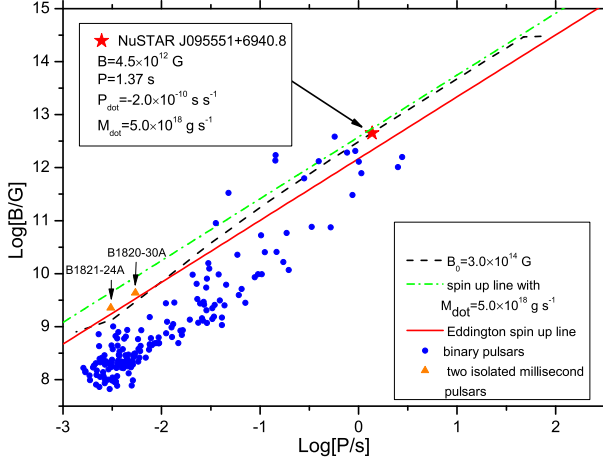


Figure 1. The diagram of the magnetic field versus spin period. The star in the figure represents the B-P position of NuSTAR J095551+6940.8, which is plotted with our computation of $B = 4.5 \times 10^{12}$ G, $\dot{M} = 5.0 \times 10^{18}$ g s $^{-1}$ and the observed spin period $P = 1.37$ s. The dash line represents the simulated evolutionary path of NuSTAR J095551+6940.8 with the initial field of 3.0×10^{14} G and spin period of 100 s, as depicted in the figure. The dash-dotted line and solid line are the spin up line with the accretion rate $\dot{M} = 5.0 \times 10^{18}$ g s $^{-1}$ and the Eddington accretion rate, respectively. With the data from ATNF pulsar catalogue (Manchester et al. 2005), we plot the B-P position of observed binary pulsars with dots and two isolated millisecond pulsars above the Eddington spin up line with triangles.

In order to calculate the present magnetic field of NuSTAR J095551+6940.8, the spin period $P = 1.37$ s and period derivative $\dot{P} \approx -2 \times 10^{-10}$ s s $^{-1}$ are used in Eq.(4). We find that the simulated model curve in the B-P diagram (Fig.1) requires the accretion rate to be $\dot{M} = 5.0 \times 10^{18}$ g s $^{-1}$, and the obtained magnetic field is $B = 4.5 \times 10^{12}$ G. For such a result, the B-P position of NuSTAR J095551+6940.8 is included in its evolutionary path. From the B-P evolutionary history, the source might accrete $\sim 0.005 M_{\odot}$ within about 10^5 yr, which feeds the field reduction and spins up the magnetar to the present state. The fastness parameter is $\omega_s = \Omega_s/\Omega_k \approx 0.46$, by which we get the parameter $\omega_s/\omega_c = 0.51$ under the condition of the critical value ω_c being 0.9 (Ghosh & Lamb 1992). The value of the fastness parameter is less than ω_c which means NuSTAR J095551+6940.8 is now in the spin-up process. As the continuing decreasing of the spin period, ω_s increases to the critical spin period ω_c and the spin-up torque vanishes.

4 DISCUSSION AND CONCLUSION

4.1 The evolutionary history of NuSTAR J095551+6940.8

We deduce that NuSTAR J095551+6940.8 could be an evolving magnetar which is now spinning up. With the initial magnetic field and spin period ($B_0 \sim 3.0 \times 10^{14}$ G and $P_0 \sim 100$ s), the simulation shows that the current magnetic field of NuSTAR J095551+6940.8 has been deduced to 4.5×10^{12} G with $\dot{M} = 5.0 \times 10^{18}$ erg s $^{-1}$ in about 10^5 yr, while the accretion material is about $0.005 M_{\odot}$. The subsequent evolution of NuSTAR J095551+6940.8 depends on its companion mass. In the binary system, the B-P evolution of a NS is mainly affected by the companion mass, which is associated with the accretion lifetime (Pan et al. 2013). The companion mass of NuSTAR J095551+6940.8 is more than $5.2 M_{\odot}$ (Bachetti

et al. 2014), which will lead to two kinds of possible evolutionary descendants:

(a) If the companion is a $5.2 - 8 M_{\odot}$ star, the disk accretion can last $\sim 10^7$ yr. The accretion material will be about $0.2 M_{\odot}$ which can make NuSTAR J095551+6940.8 to be a millisecond pulsar with the polar magnetic field of 10^9 G and the spin period about 10 ms, while the super-strong out-polar field is squeezed into the NS core region. There will be a millisecond pulsar and a heavy white dwarf left in the binary system after the accretion.

(b) If the companion is a $> 8 M_{\odot}$ star, the NS may accrete about $\sim 0.02 M_{\odot}$ within $\sim 10^6$ yr. A double NS system will exist at the end of the accretion, where the recycled pulsar is similar to the Hulse-Taylor pulsar PSR 1913+16 with the dipole magnetic field of $\sim 10^{10}$ G and spin period of ~ 50 ms.

4.2 The B-P path of NuSTAR J095551+6940.8

The evolutionary track of NuSTAR J095551+6940.8 in the B-P diagram above the Eddington spin-up line has been simulated (the dash line in Fig.1). From the theoretical consideration, the distribution of binary pulsars should be below the Eddington spin up line (Pan et al. 2015), since the minimum spin period of binary pulsar is arisen by the equilibrium period line with the Eddington accretion rate. However, the radio observations show that 9 binary pulsars (out of 250 ones) lie above the Eddington spin-up line (see Fig.1 in this paper, also see Fig.4 in Pan et al. 2013). We proposed that some of the 9 binary pulsars have experienced the similar evolutions with the super-Eddington accretion to that of NuSTAR J095551+6940.8. That is to say, some of them may be the descendants of magnetars after accretion. Moreover, the evolved track of NuSTAR J095551+6940.8 can also be used to explain the formation of the millisecond pulsar with the magnetic field as high as $\sim 10^{9.5}$ G, e.g., two isolated millisecond pulsars B1821-24A and B1820-30A marked in Fig.1, whose companions are believed to be evaporated after formations (Hessels 2008; Kluzniak 1988).

Now, we may have a whole picture of the evolutionary history of accreting NS in the B-P diagram: NS in high mass X-ray binary system and NS in low mass X-ray binary system evolve to the recycled pulsars below the Eddington spin-up line, while the descendants of ultra-luminous accreting magnetars stop at the B-P positions above the Eddington spin-up line, from where they begin their further spin-down evolutions by electromagnetic emission.

4.3 The birth rate of ultra-luminous NS in HMXBs

The birth rate of magnetar is about 10% compared with that of normal NSs (Lorimer 2008), so the number of accreting magnetar systems shown as the ultra-luminous neutron star in HMXBs should be also $\sim 10\%$ of the normal NS in HMXBs. Moreover, from the radio observations, only 9 of 250 binary pulsars lie above the Eddington spin-up line, thus we infer that the ratio of accreting magnetars to NS in X-ray binaries should be at the scale of 4%. Until now, about a hundred of X-ray NS binary systems are observed (Liu et al. 2007). Therefore, it can be inferred that there would be a couple of ULXs to be accreting magnetars that are similar to NuSTAR J095551+6940.8.

4.4 The possible magnetic structure of ultra luminous NS in HMXB

Based on the model of accretion induced polar magnetic field decay of the NS (Zhang & Kojima 2006), the polar magnetic field would decay one half order of magnitude after accreting $0.0001M_{\odot}$, e.g., from $\sim 10^{13}$ G to $\sim 10^{12.5}$ G. At the same time, the out-polar field is slightly increased, which keeps almost the same as the initial value of $\sim 10^{13}$ G. For the model acquires the magnetic flux conserving globally, the dilution of the polar field lines will be compensated by the expanding out-polar field lines. The strong out-polar field lines will be totally squeezed into the NS core after accreting the mass about $0.1M_{\odot}$.

The result shows that the polar field of NuSTAR J095551+6940.8 decays about two magnitude orders, from $\sim 10^{14.5}$ G to $\sim 4.5 \times 10^{12}$ G after accreting $0.005M_{\odot}$. The out-polar field is almost unchanged compared with the initial value of $\sim 10^{14.5}$ G. The difference of the magnetic field strength between the polar region and equator region will intensely arise the asymmetry of the magnetic field structure of the NS, which makes the accretion structure of the evolved magnetar in HMXB far from the spherical geometry. The Eddington luminosity, which requires a condition of the spherical accretion (Shapiro & Teukolsky 1983; Frank et al. 2002), will be destroyed by the exotic magnetic field structure. In addition, the super-strong multipole field structure induces the reduction of the scattering cross section of photon-electron, and in turn increases the Eddington critical luminosity (Eksi et al 2015; Laycock et al. 2015).

4.5 Origin of the ultra luminosity of magnetar in HMXB

In the simulation, the accretion rate $\dot{M} = 5.0 \times 10^{18} \text{ g s}^{-1}$ is obtained by consisting the observed spin period and derivative of NuSTAR J095551+6940.8 with the calculation values. To settle the ultra luminosity difficulty, we propose two types of accretions for magnetar in HMXB, i.e., the radial random accretion \dot{M}_r without bringing orbital angular momentum and the disk accretion \dot{M}_d that contributes to the NS spin-up, thus the total accretion rate can be divided into two components,

$$\dot{M} = \dot{M}_r + \dot{M}_d. \quad (7)$$

The components of the two type accretions should be correlated to the NS magnetic structure, disk thickness and accretion environment. For the usual NS in HMXB, the two accretion components are comparable $\dot{M}_r \sim \dot{M}_d$, so the source luminosity is comparable with the disk accretion luminosity $L_x \sim L_{\text{acc}}$, which is no bigger than the Eddington limit. However, for the magnetar as an ULX in HXMB, the local super-strong field destroys the spherical accretion geometry and breaks the limit of the Eddington luminosity. The structure of the super strong multipole field dominates the radiation mechanism and leads the emission to be beamed. So, the beaming factor b can be introduced for the accretion luminosity L_{acc} that is associated with the X-ray luminosity L_x : $L_{\text{acc}} = bL_x$, where $b < 1$ (Feng and Soria, 2011). For ULX NuSTAR J095551+6940.8, when assuming the pulsed fraction to be 0.05 (King and Lasota, 2016), then the accretion rate $5.0 \times 10^{18} \text{ g s}^{-1}$ of the simulation would be reasonable to infer the radial random accretion rate as $\dot{M}_r = (1/b)\dot{M}_d = 20\dot{M}_d$, which can account for the observed ultra luminosity ($1.8 \times 10^{40} \text{ erg s}^{-1}$) of the source. Therefore, the source accretes about $10^{-2.5}M_{\odot}$ through the polar channel as calculated from the simulation, which implies $\sim 2 \times 10^{-1.5}M_{\odot}$ to be accreted through the non-polar random accretion.

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